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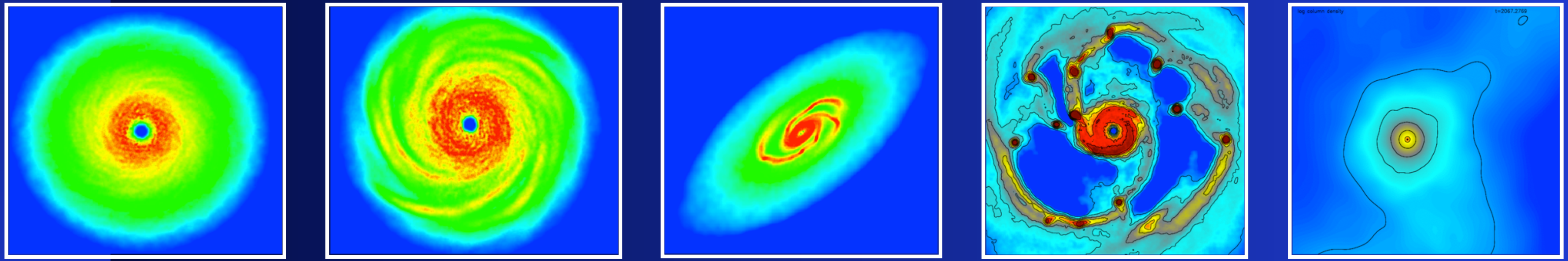
Dimitris Stamatellos
School of Physics & Astronomy
Cardiff University, Wales, UK

The formation of low-mass stars and brown dwarfs by disc fragmentation

11th October 2011, ESO, Germany



D.Stamatellos@astro.cf.ac.uk
http://www.astro.cf.ac.uk/pub/Dimitrios.Stamatellos

The formation of low-mass stars and brown dwarfs

- **gravo-turbulent fragmentation of molecular clouds**

  Padoan & Nordland 2002; Bate et al. 2004; Goodwin et al. 2004
  Hennebelle & Chabrier 2008, 2010

- **premature ejection of protostellar embryos**

  Clarke & Reipurth, Bate et al. 2003, 2004; Goodwin et al. 2004

- **disc fragmentation**

  Stamatellos, Hubber & Whitworth 2007, MNRAS
  Stamatellos & Whitworth 2009, MNRAS, Bate et al. 2003

Brown dwarf and low-mass star formation by disc fragmentation

Stamatellos & Whitworth 2009, MNRAS, 392, 413
"The properties of brown dwarfs and low-mass hydrogen-burning stars formed by disc fragmentation"

✔ The shape the low-mass end of the IMF

✔ The presence of discs around brown dwarfs (BDs don't have to form like solar-mass stars in order to have discs!)

✔ The formation of BD-BD binaries (produce both tight and wide binaries)

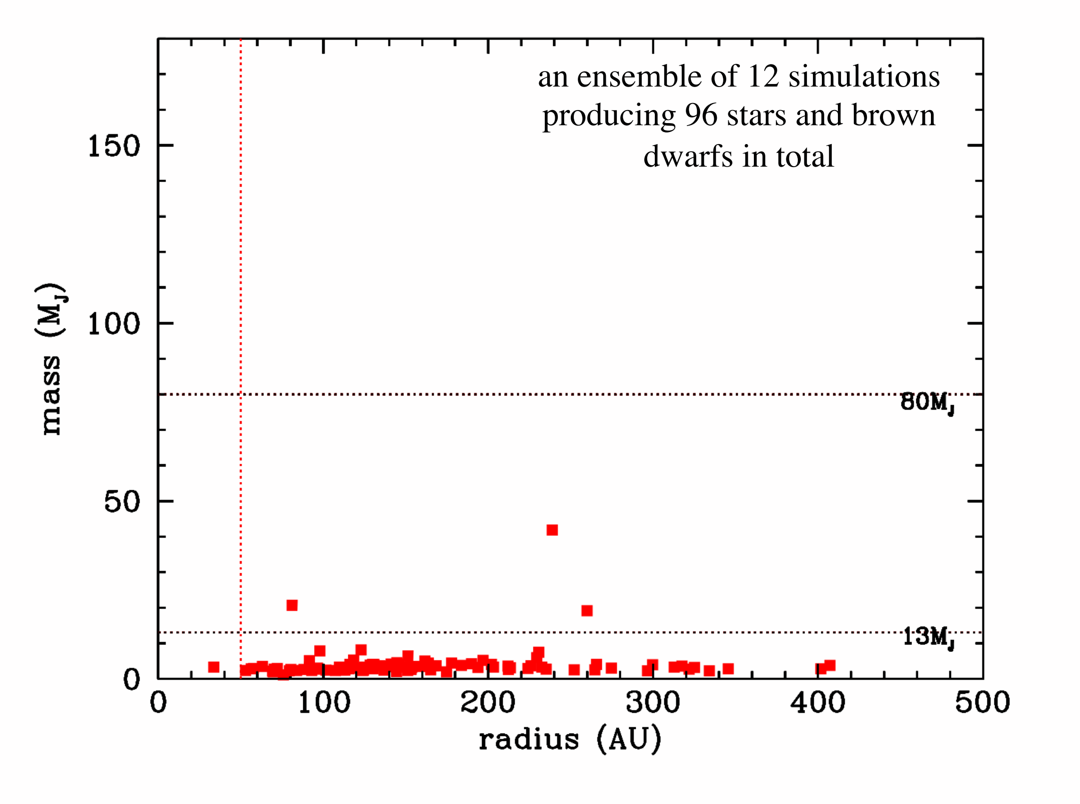
✔ The formation of free-floating planetary-mass objects

✔ Specific low-mass binary characteristics: BDs that are companions to Sun-like stars are more likely (25-50%) to be in binaries than brown dwarfs in the field (~10%) (Burgasser et al. 2005; Faherty et al. 2010)

✔ The brown dwarf desert

The brown dwarf desert: where did the brown dwarfs go?

- There are many planets and low-mass stars close (<5 AU) companions to Sun-like stars, but almost no brown dwarfs (Marcy & Butler 2000) .
- The brown dwarf desert may extend out to ~1000 AU (Gizis et al. 2001) but is less “dry” of brown dwarfs outside ~50 AU (Neuhauser et al. 2003).



time ~ 5,000 yr

- Rafikov 2005
- Matzner & Levin 2005
- Whitworth & Stamatellos 2006

Fragmentation can happen only at radii larger than ~70-100 AU

The brown dwarf desert: where did the brown dwarfs go?

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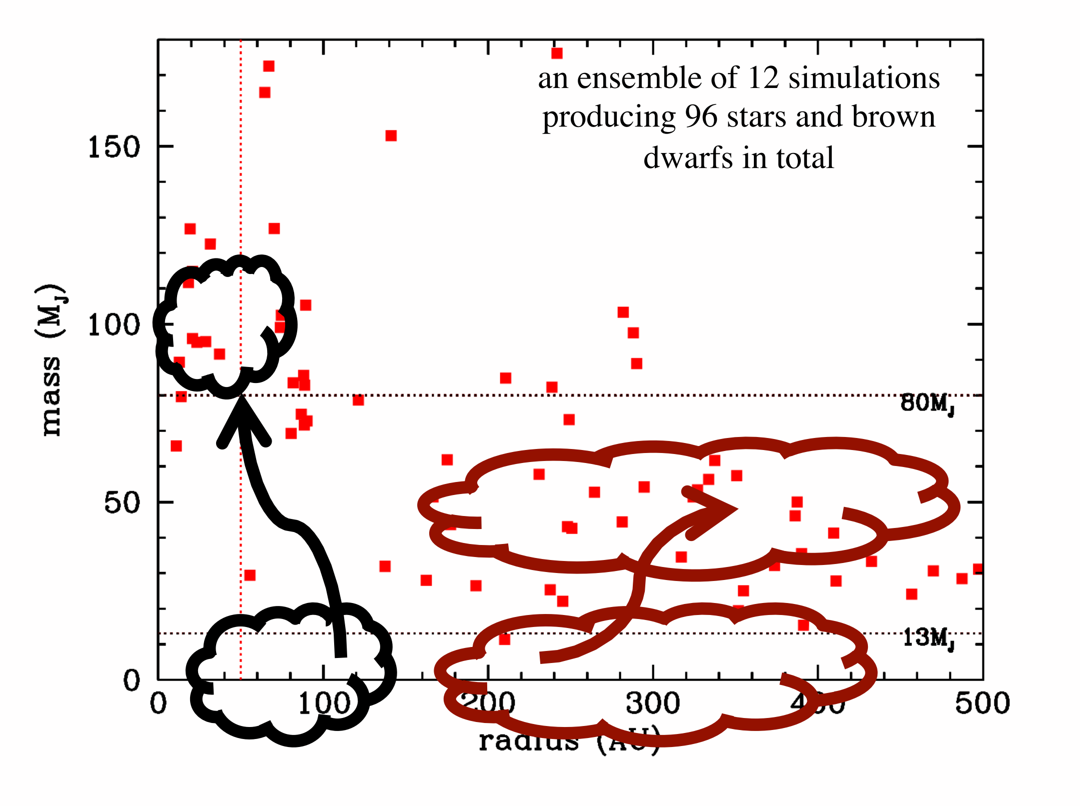

time ~ 20,000 yr

The brown dwarf desert: where did the brown dwarfs go?

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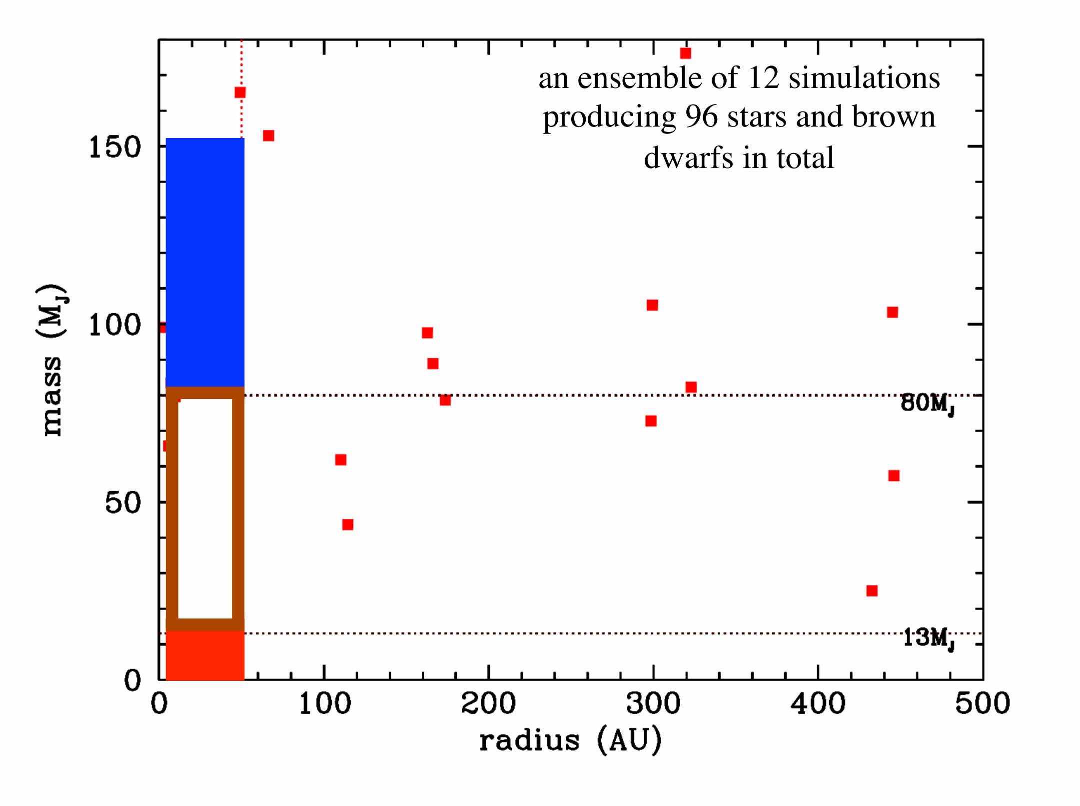
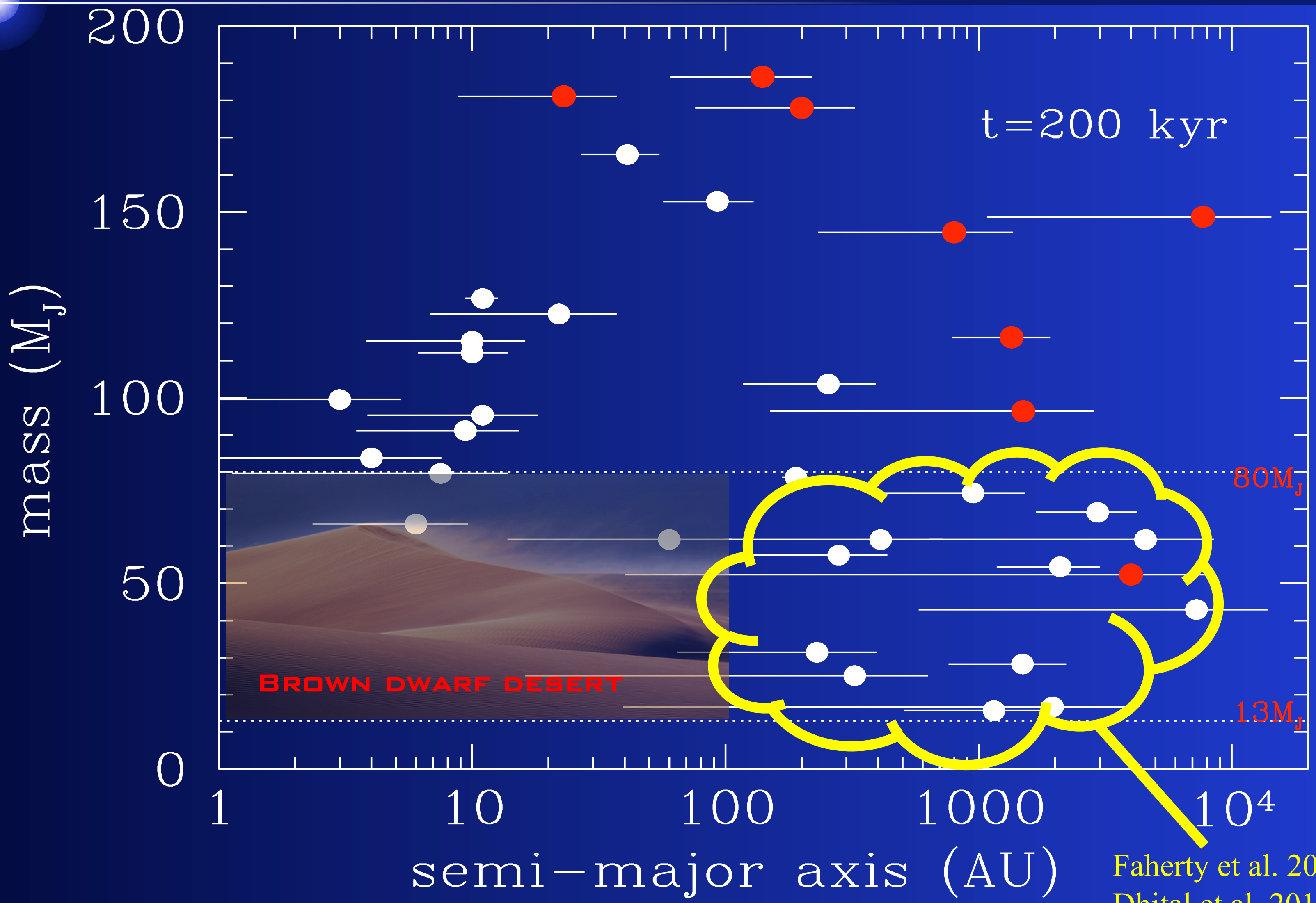
- The brown dwarf desert may extend out to ~1000 AU (Gizis et al. 2001) but is less “dry” of brown dwarfs outside ~50 AU (Neuhauser et al. 2003).



time ~ 200,000 yr

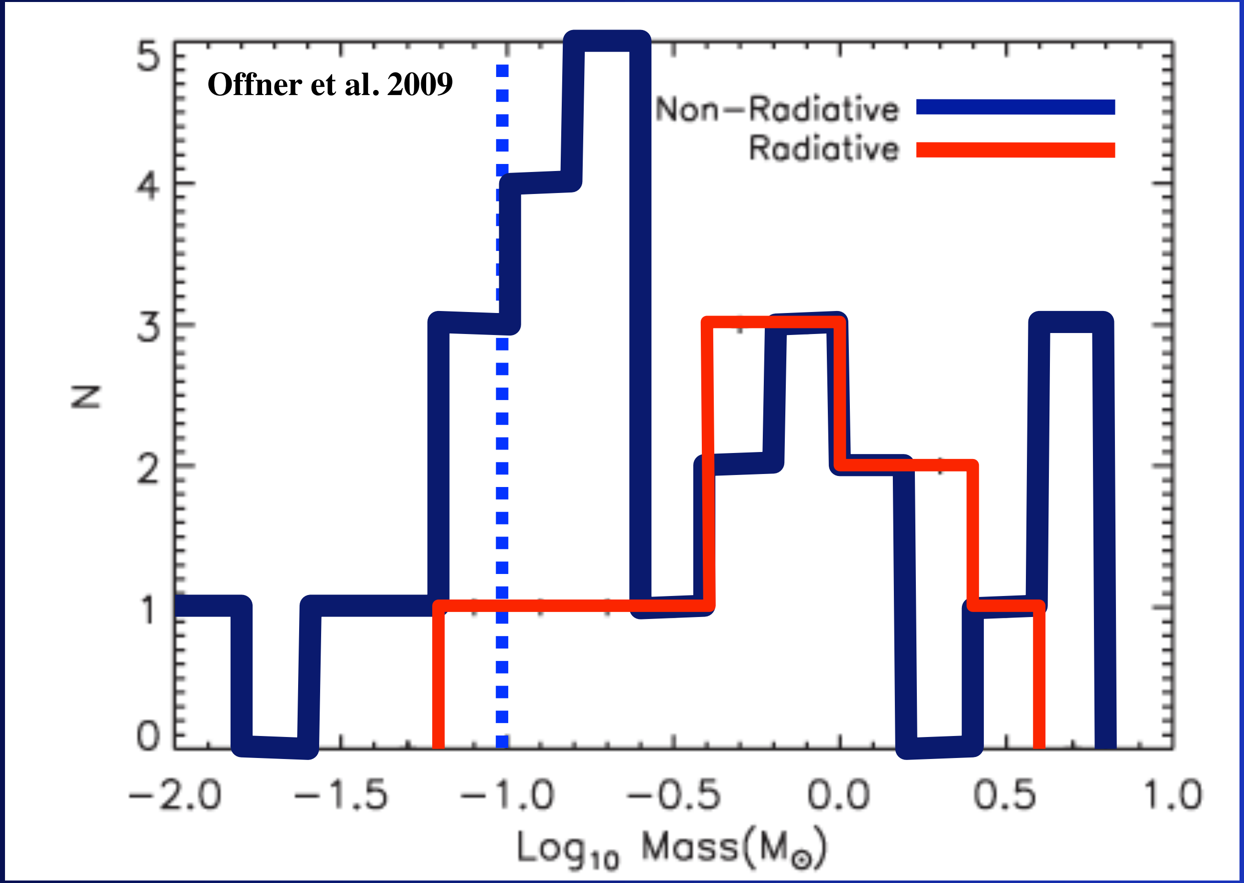
The brown dwarf desert: where did the brown dwarfs go?



Faherty et al. 2009
Dhital et al. 2010
Zhang et al. 2010

Radiative feedback suppresses the formation of low-mass stars and brown dwarfs?

- Offner et al. 2009; Bate 2009, 2011



- Almost no brown dwarfs form at all → something is missing

The importance of radiative feedback from protostars

Simulation I:

Radiative feedback is included down to the sink radius (1AU)

[similar to Bate's 2009 simulations]

Initial conditions: turbulent cloud core

$$M = 5.4 M_{\odot} \qquad N_{\mathrm{SPH}} = 10^6 \text{ particles}$$

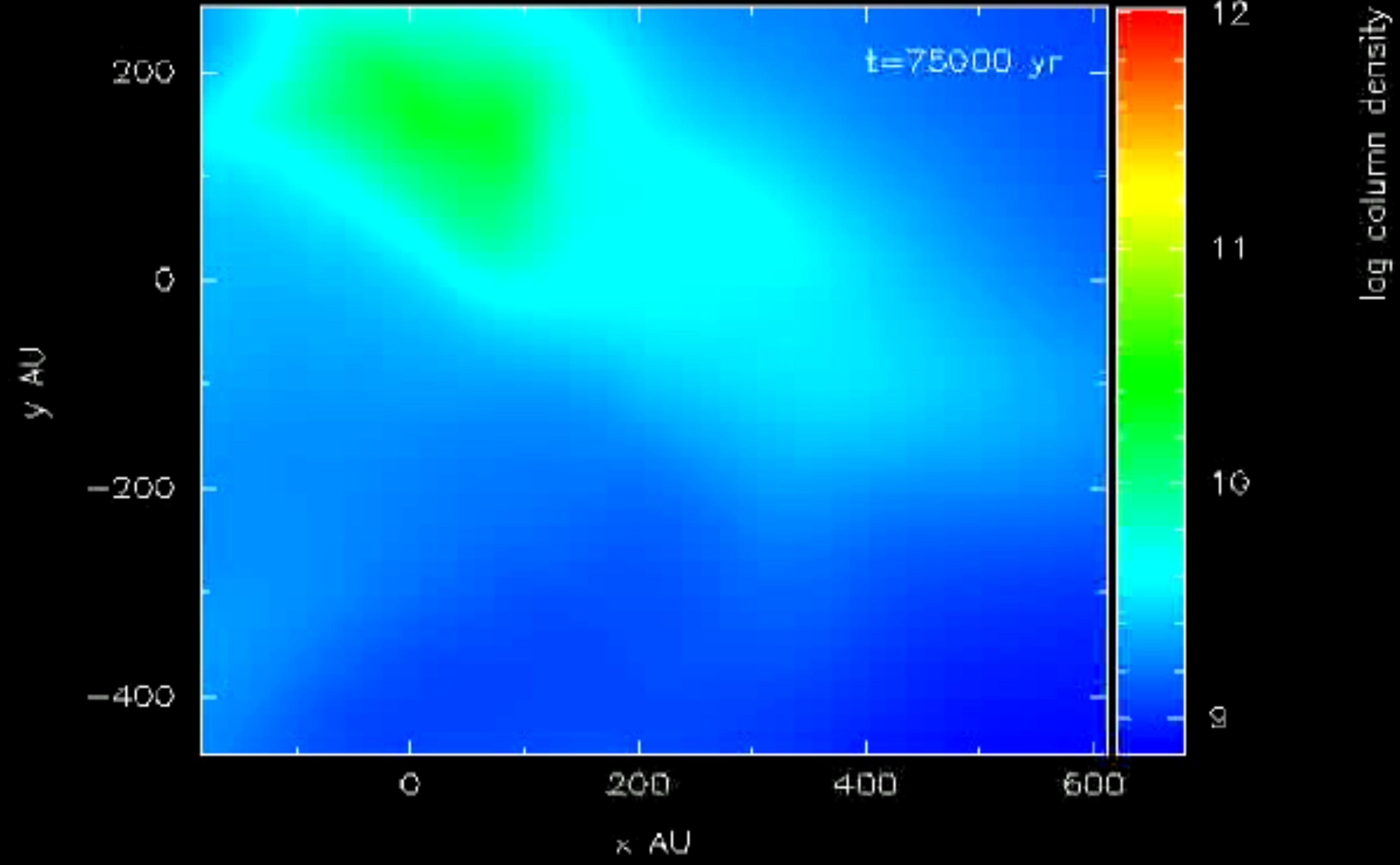
$$\rho(r) = \frac{\rho_{\mathrm{kernel}}}{(1 + (r/R_{\mathrm{kernel}})^2)^2}$$

$$R_{\mathrm{KERNEL}} = 5000 \text{ AU}$$

$$\rho_{\mathrm{KERNEL}} = 3 \times 10^{-18} \text{ g cm}^{-3}$$

$$R_{\mathrm{CORE}} = 50\,000 \text{ AU}$$

- SPH code SEREN by David Hubber et al. (2011)
- Radiative transfer method of Stamatellos et al. (2007)


t=75000 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
12
11
10
9
log column density

The importance of radiative feedback from protostars

Simulation II:

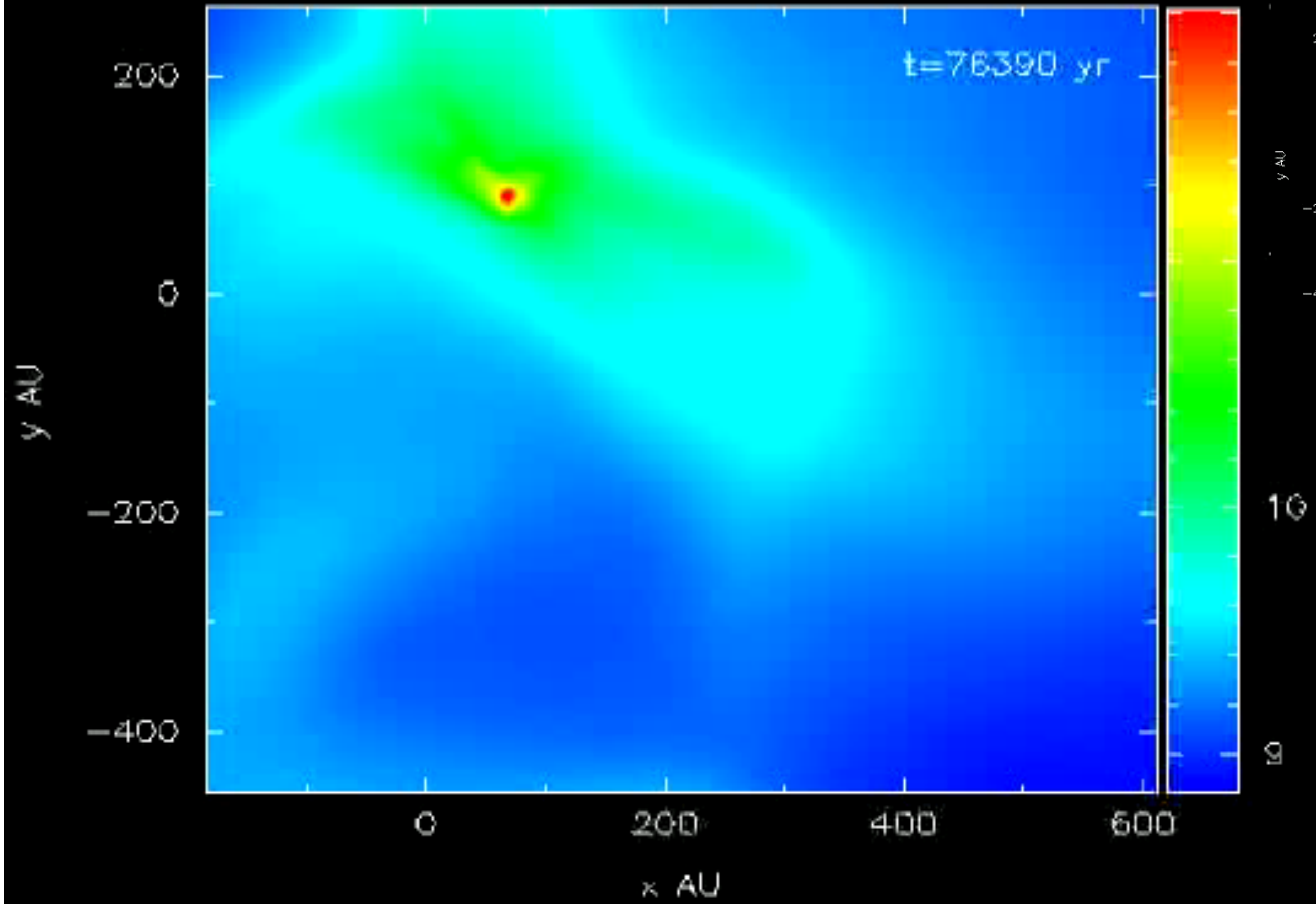
Radiative feedback from protostars is fully included

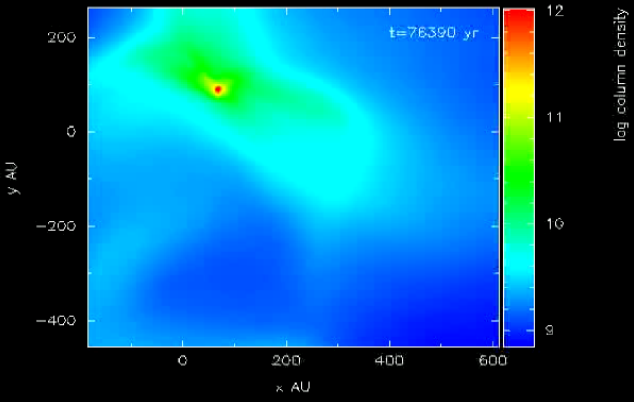
Continuous radiative feedback

[similar to Offner, Krumholz, Klein 2009 simulations]

$$L_\star = \left(\frac{M_\star}{\mathrm{M}_\odot}\right)^3 \mathrm{L}_\odot + f_{\mathrm{rad}} \frac{G M_\star \dot{M}_\star}{R_\star} \left(1 - \frac{R_\star}{2 R_{\mathrm{sink}}}\right)$$

$f_{\mathrm{rad}} = 0.75$ The fraction of the accretion energy that is radiated away


t=76390 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
10
9


t=76390 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
12
11
10
9
log column density

Accretion is episodic: FU Ori's

[see talks by Dunham, Hartmann, Offner]

- FU Ori-type stars

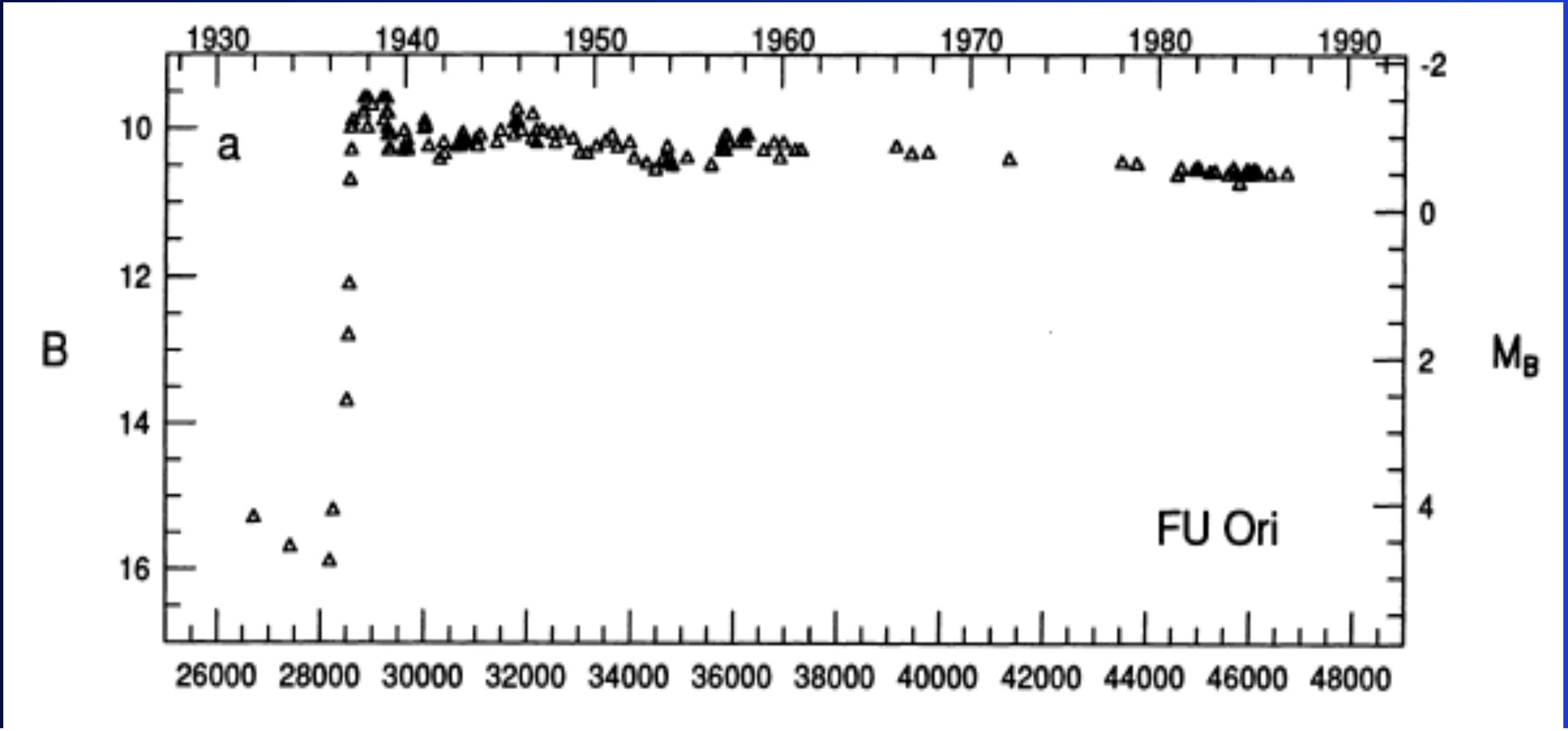
Hartmann & Kenyon 1996, ARAA

rise time: 1-10 yr

duration: 10s to a few 100s yr

Accretion rate: a few 10^{-4} $M_{\odot}$/yr

Mass: 0.01-0.1 $M_{\odot}$/event



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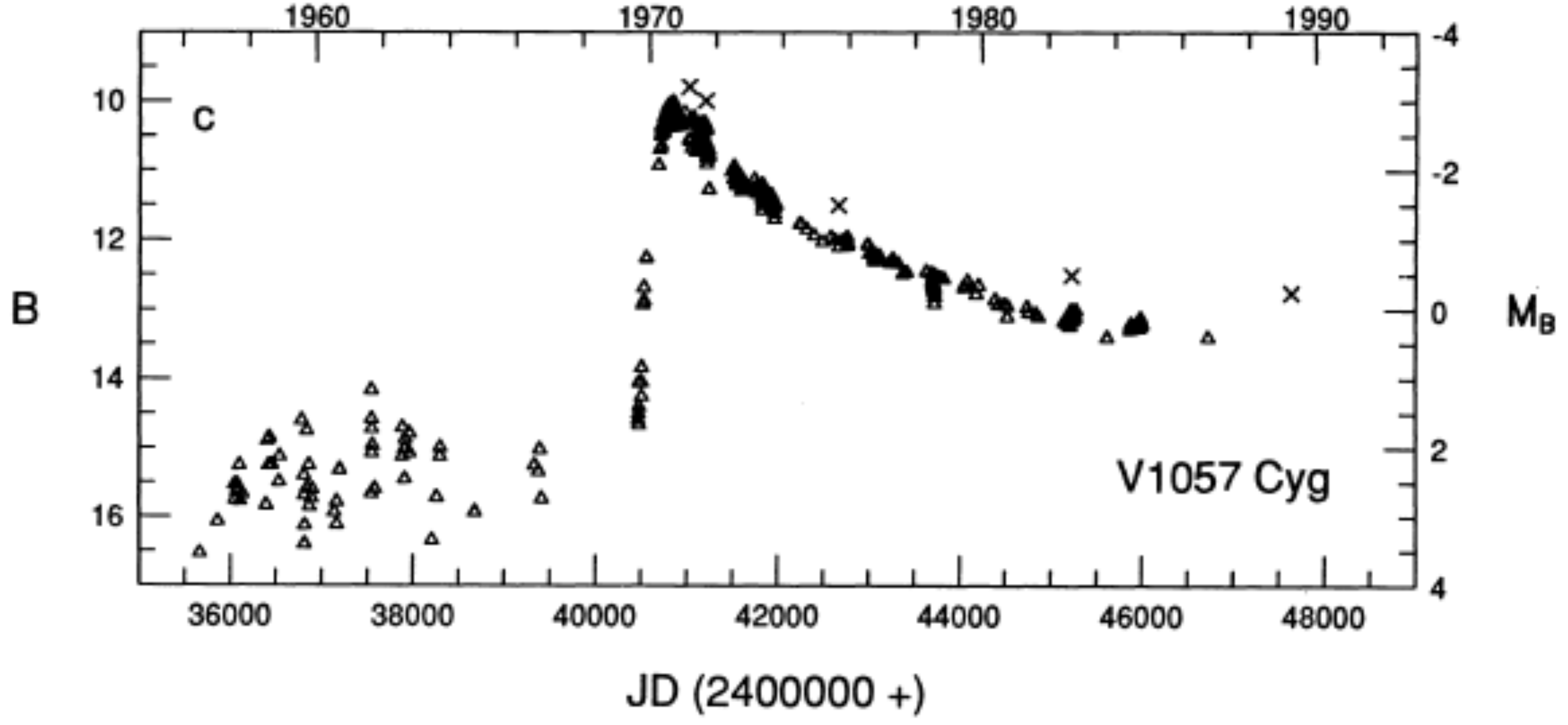
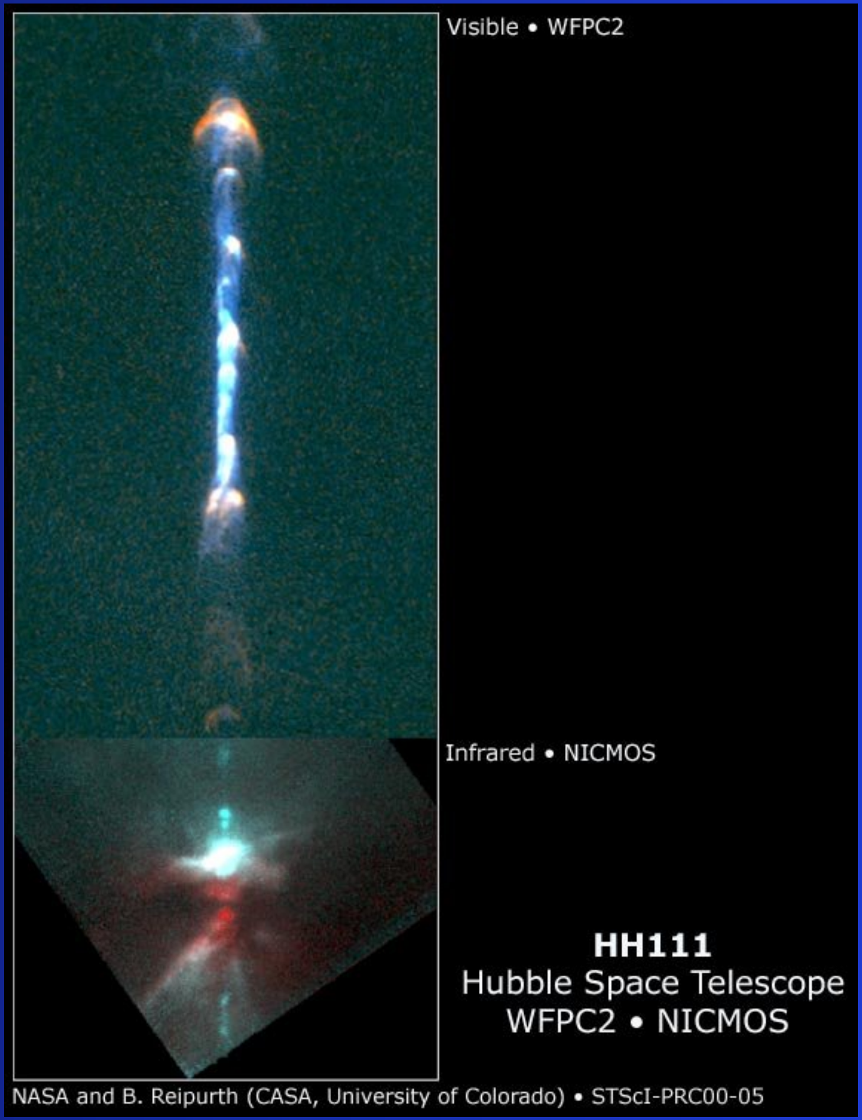


Accretion is episodic: Herbig-Haro objects

- Episodic accretion onto a protostar results in episodic ejection of material.

Reipurth Nature 340, 42–45(1989)



NASA and B. Reipurth (CASA, University of Colorado) • STScI-PRC00-05

Accretion is episodic: the luminosity problem

- The luminosities of protostars are not high enough (Kenyon et al. 1990; Evans et al. 2009; Dunham et al. 2010)

$$0.5\mathrm{M}_\odot/10^5\mathrm{yr} \rightarrow \dot{M} = 5 \times 10^{-6} M_\odot \mathrm{yr}^{-1} \rightarrow L = \frac{GM\dot{M}}{R_\star} \approx 25 L_\odot$$

- FU Ori type outbursts may happen for all protostars providing a solution to the luminosity problem :the luminosity is very high only during short events

The case for episodic accretion

- Thermal instability (Bell & Lin 1994)
- Binary companion (Bonnell & Bastien)
- Gravitational instabilities (Vorobyov & Basu 2005, 2006)
- Planet "blocking" (Lodato & Clarke 2004)

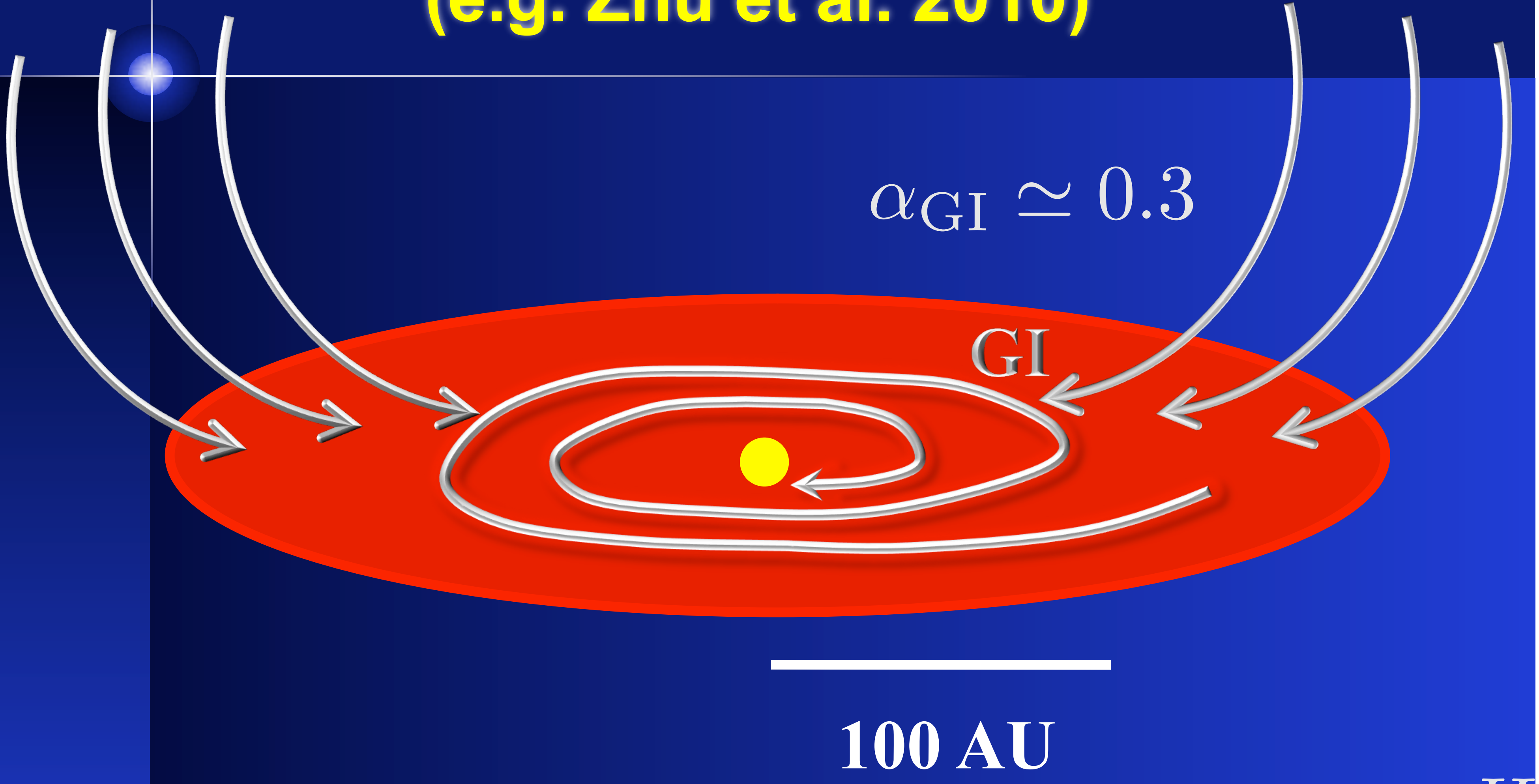
- Zhu, Hartmann et al. 2008-2010: The combined effect of different angular momentum transfer efficiencies of the gravitational instability (GI) and magneto-rotational instability (MRI).

GI: works better >10 AU from the star

MRI: works better at <1 AU

MRI is initiated when **T_M>1400 K** in the inner disc region and the outburst starts. Stops when temperarture drops again.

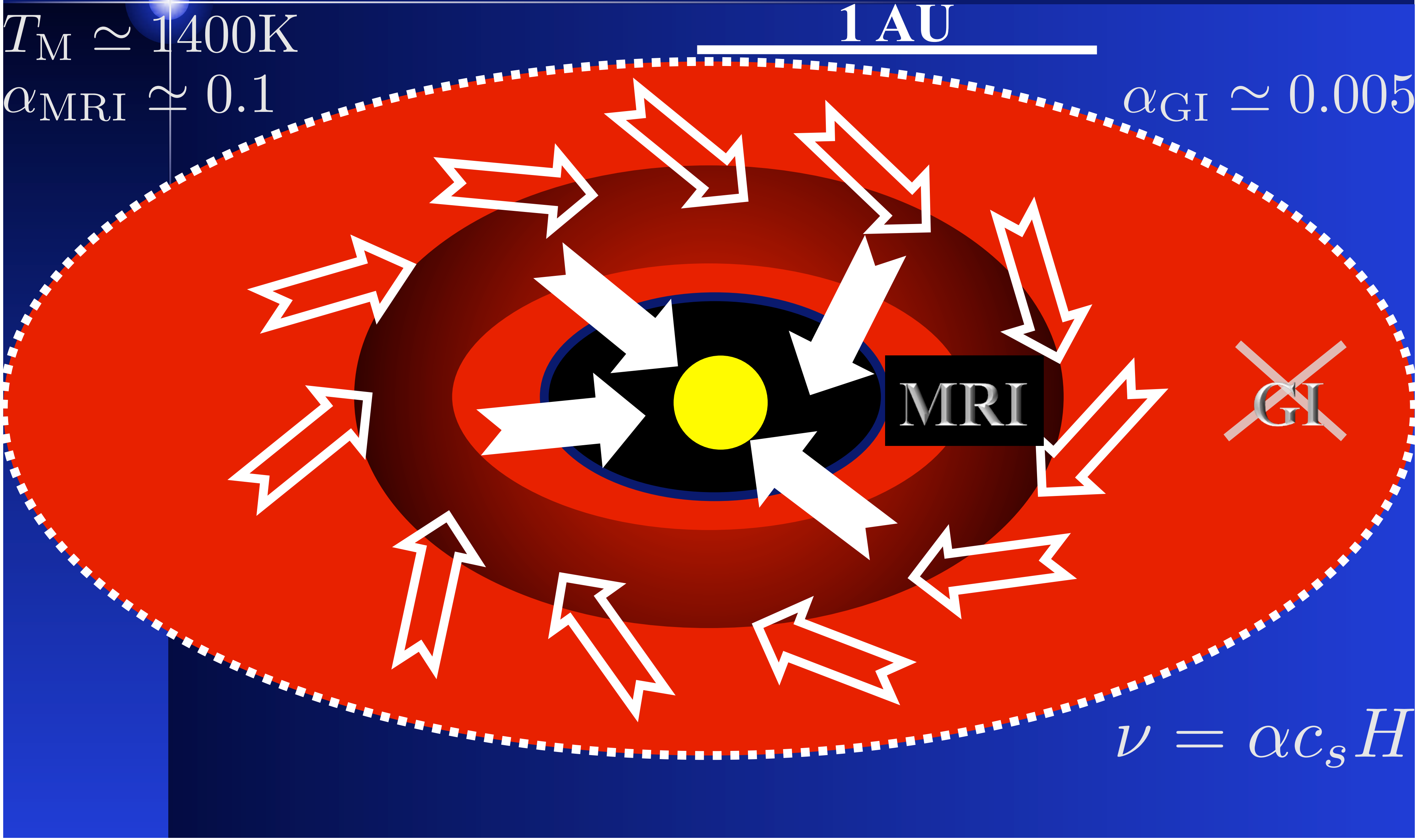
Episodic accretion: GI & MRI (e.g. Zhu et al. 2010)



$$\alpha_{\mathrm{GI}} \simeq 0.3$$

$$\nu = \alpha c_s H$$

Episodic accretion: GI & MRI
(e.g. Zhu et al. 2010)



$T_{\mathrm{M}} \simeq 1400\mathrm{K}$

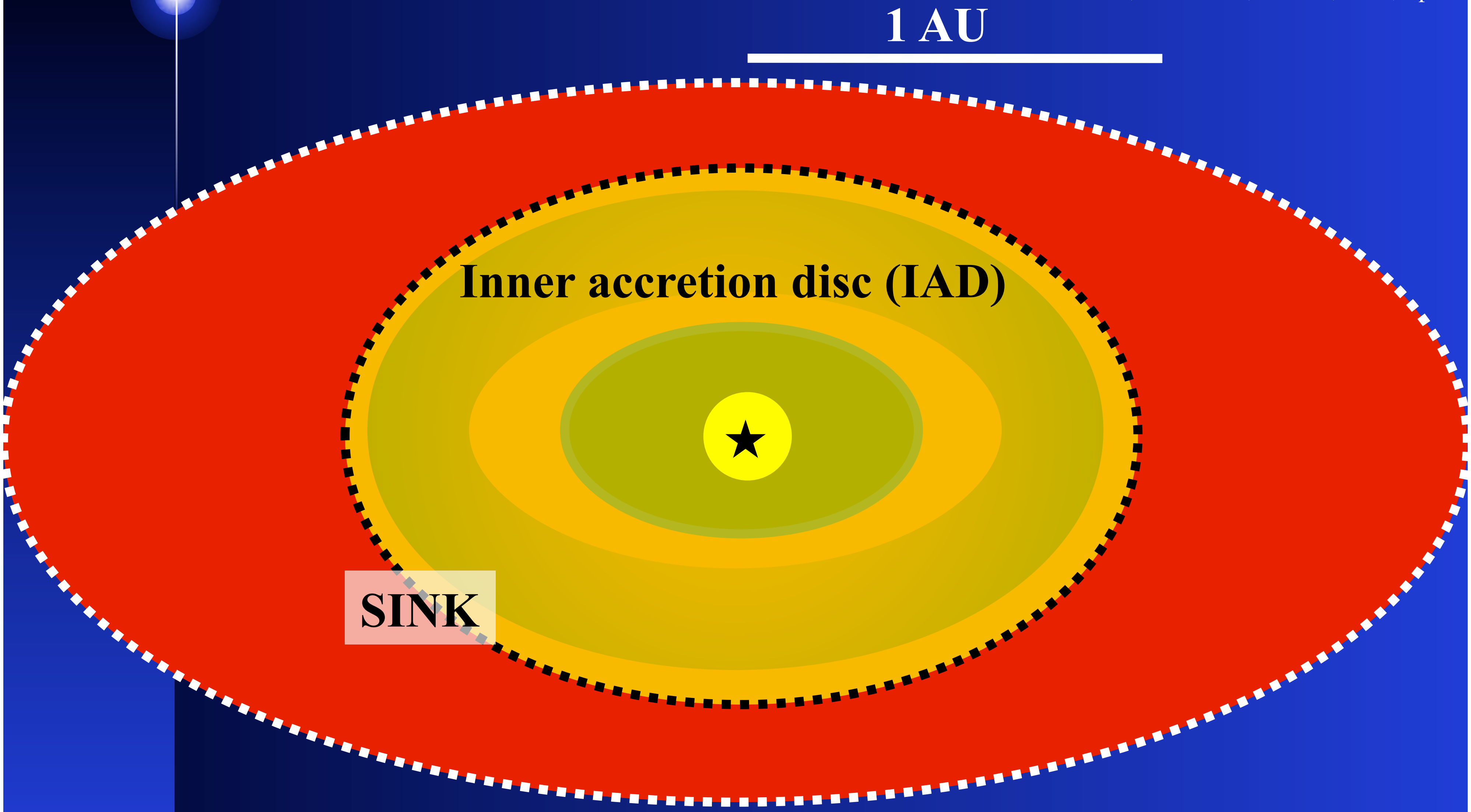
$\alpha_{\mathrm{MRI}} \simeq 0.1$

$\alpha_{\mathrm{GI}} \simeq 0.005$

$\nu = \alpha c_s H$

A phenomenological model of episodic accretion in hydrodynamic simulations

Stamatellos, Whitworth, Hubber, 2011, ApJ



A phenomenological model of episodic accretion (based on Zhu et al. 2010)

Stamatellos, Whitworth, Hubber, 2011, ApJ

Episodic accretion is initiated when

$$M_{\rm IAD} \geqslant M_{\rm MRI} \quad (T_M = 1400 \text{ K})$$

$$M_{\rm MRI} \simeq 0.13\,{\rm M}_\odot \left(\frac{M_\star}{0.2\,{\rm M}_\odot}\right)^{2/3} \left(\frac{\dot{M}_{\rm IAD}}{10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)^{1/9}$$

Duration of an episodic accretion event

$$\Delta t_{\rm MRI} \simeq 0.25\,{\rm kyr} \left(\frac{\alpha_{\rm MRI}}{0.1}\right)^{-1} \left(\frac{M_{\rm MRI}}{0.13\,{\rm M}_\odot}\right)$$

Zhu et al. 2010a

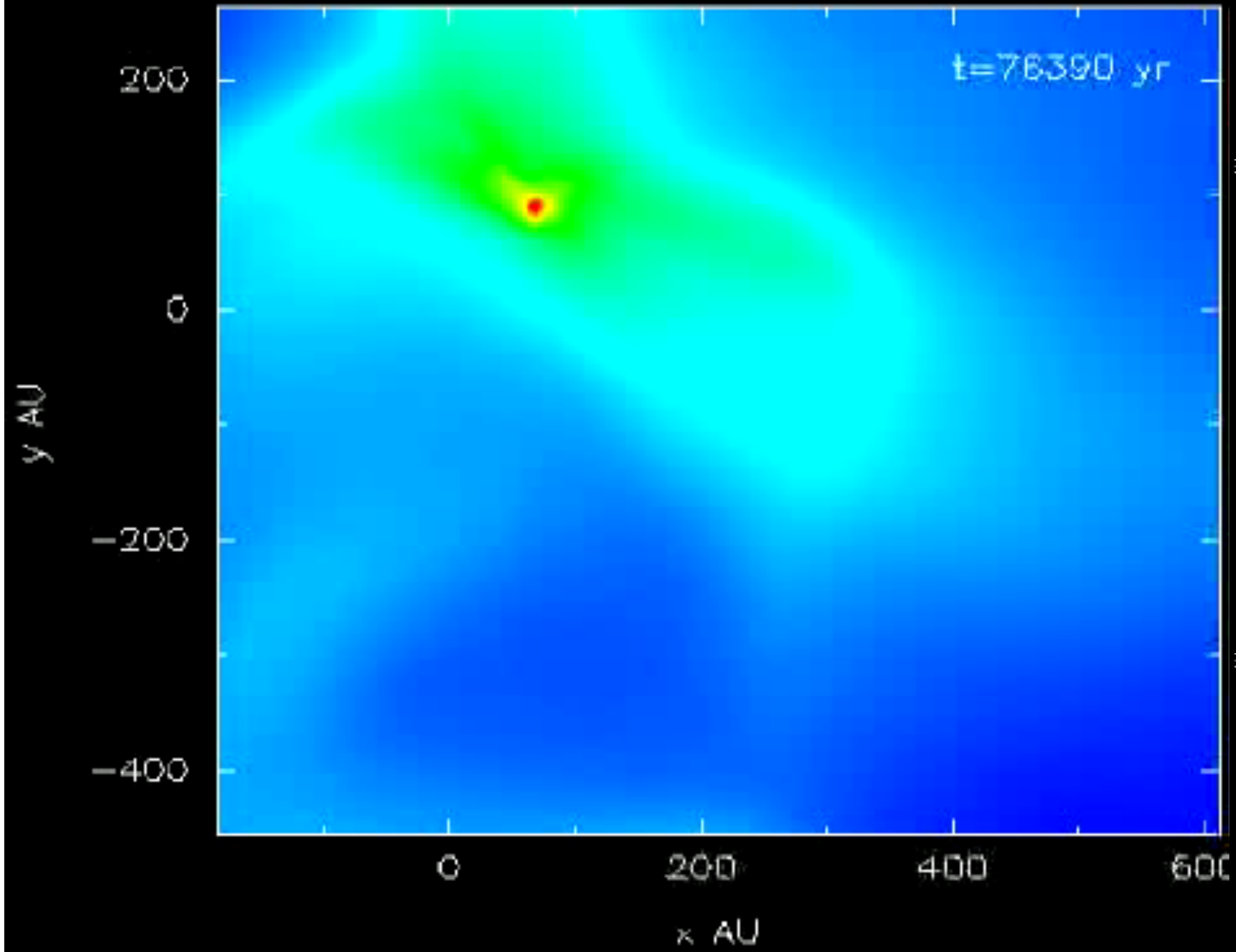
$$\dot{M}_{\star,{\rm EA}} = \frac{M_{\rm MRI}}{\Delta t_{\rm MRI}}\, e^{-\frac{(t-t_0)}{\Delta t_{\rm MRI}}}\,, \quad t_0 < t < t_0 + \Delta t_{\rm MRI}$$

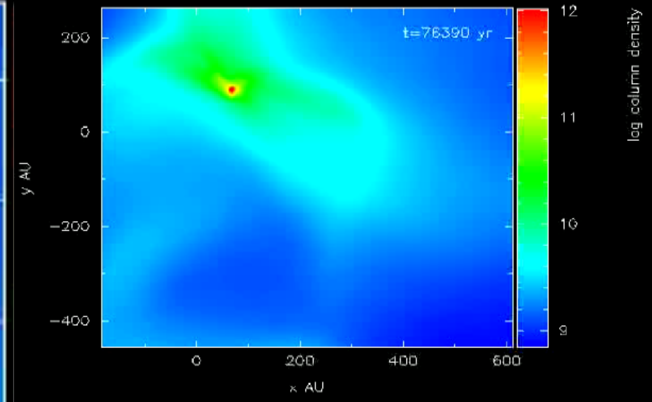
The importance of radiative feedback from protostars

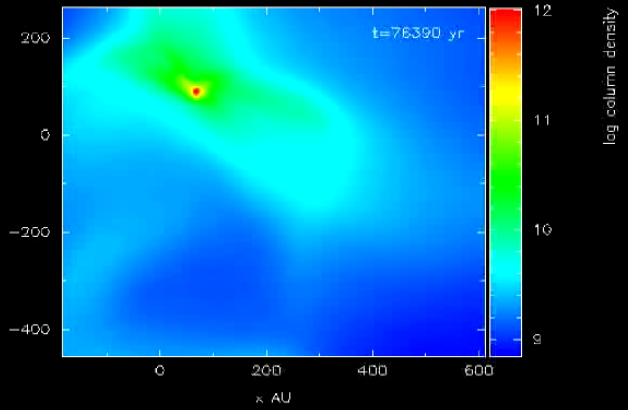
Simulation III:

Radiative feedback from protostars is fully included;

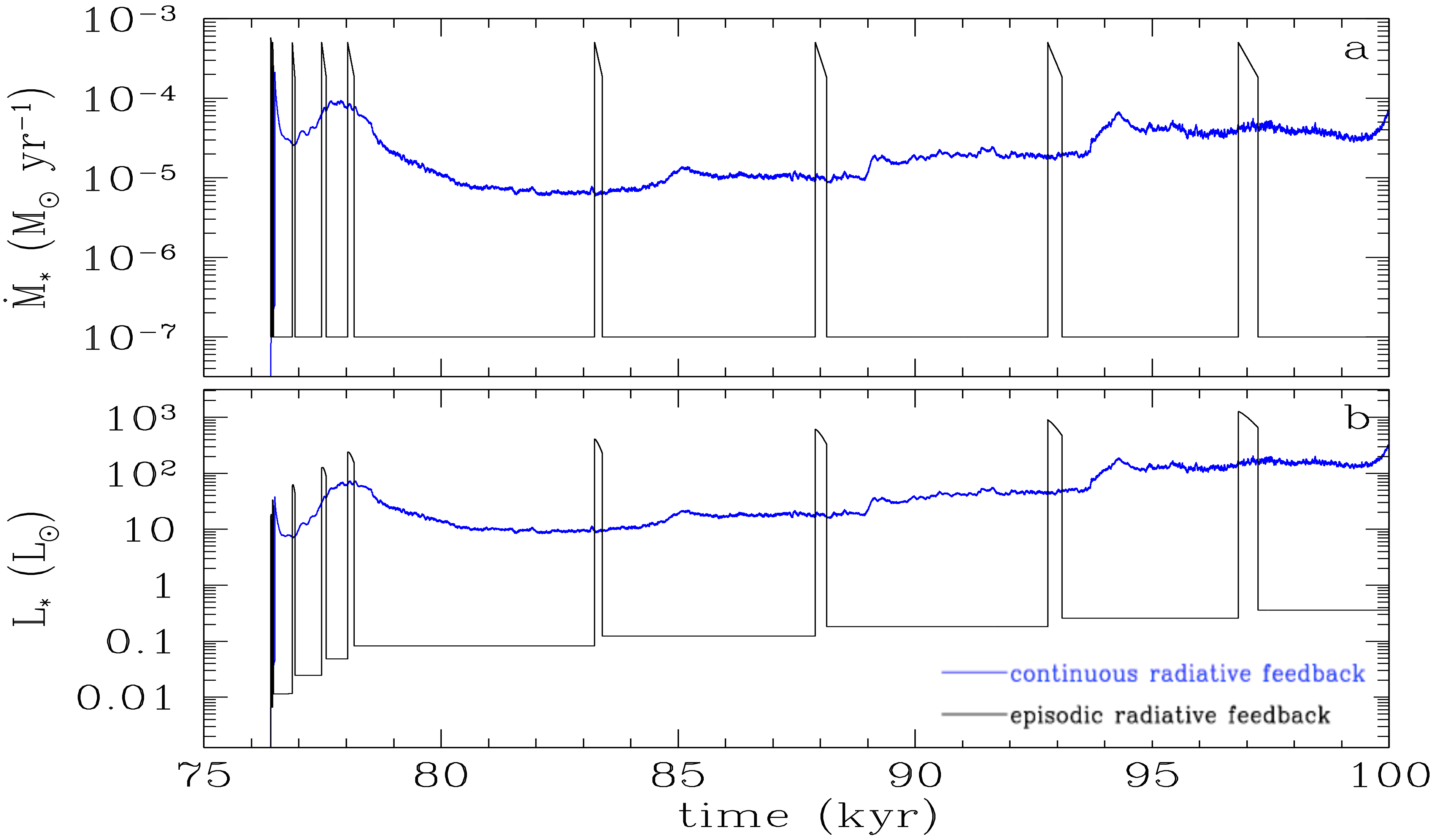
the radiative feedback is not continuous but episodic

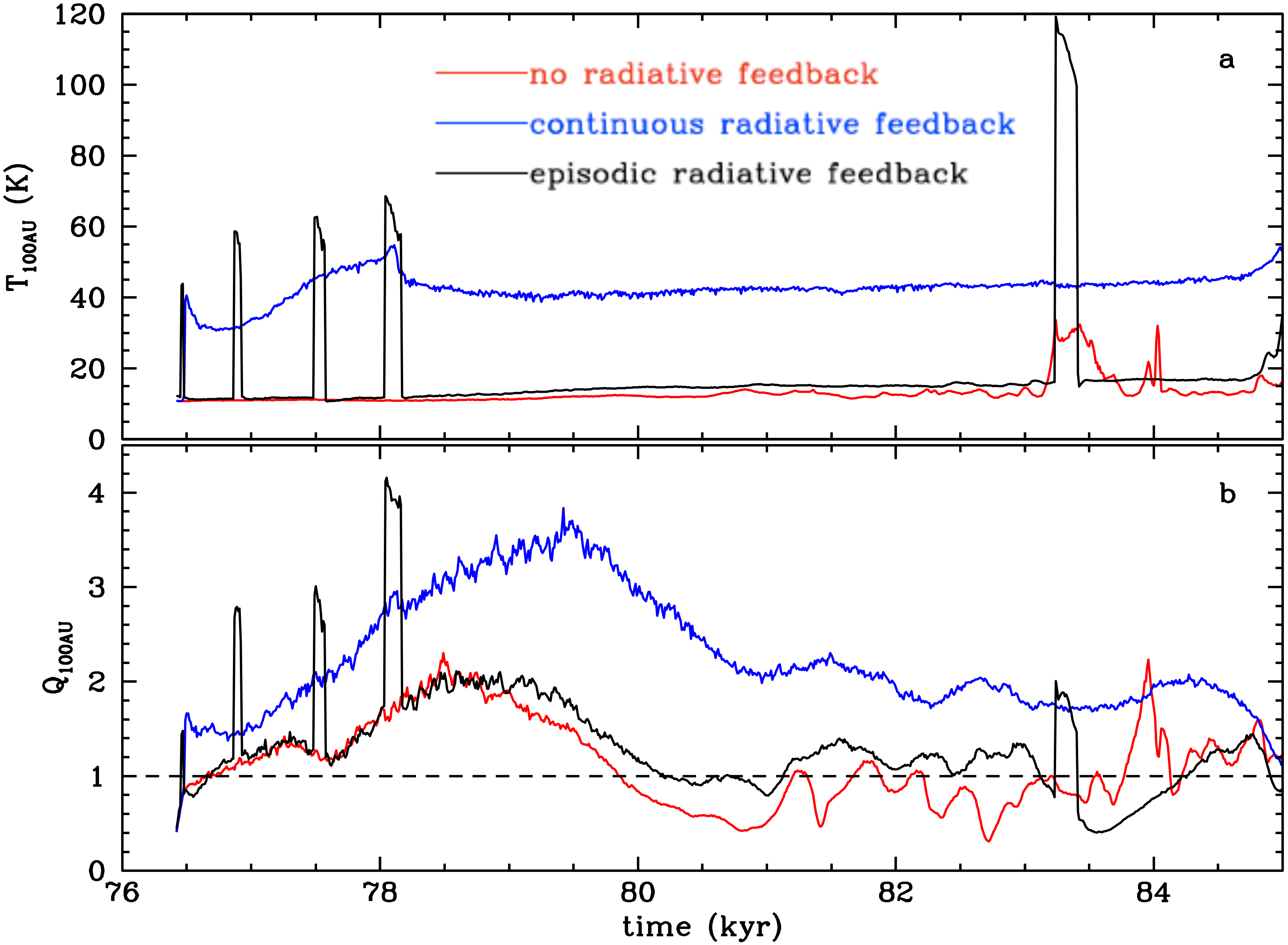

t=76390 yr
200
0
−200
−400
y AU
0
200
400
60
x AU


t=76390 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
12
11
10
9
log column density


t=76390 yr
200
0
−200
−400
y AU
0
200
400
600
x AU
12
11
10
9
log column density

Comparison
Continuous vs episodic accretion/feeback





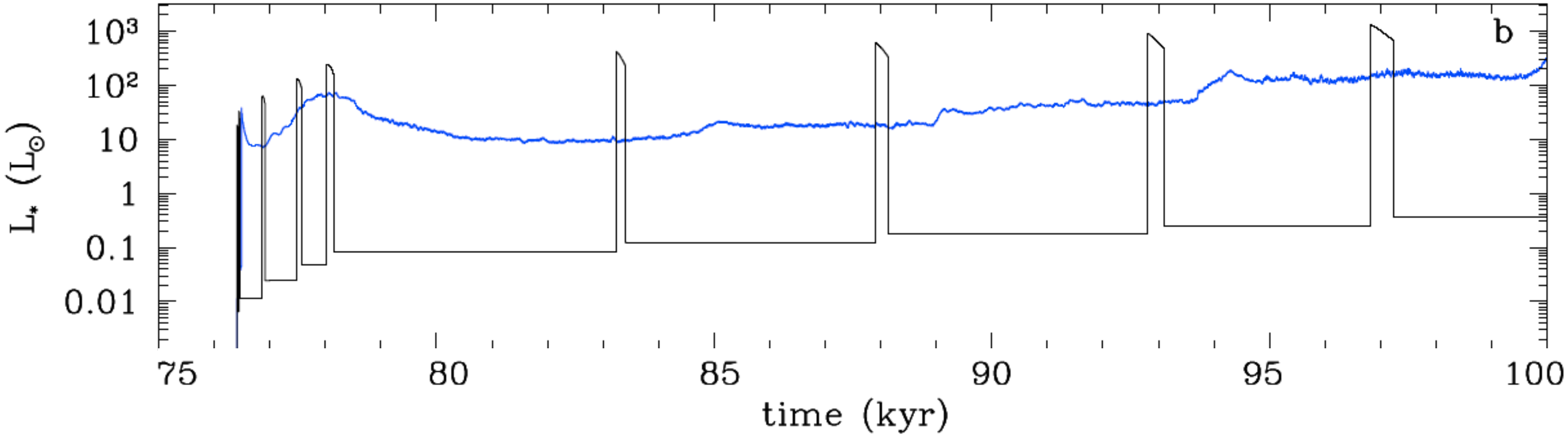
a
b
no radiative feedback
continuous radiative feedback
episodic radiative feedback
T_{100AU} (K)
Q_{100AU}
time (kyr)
0
20
40
60
80
100
120
0
1
2
3
4
76
78
80
82
84

The role of episodic accretion in low-mass star formation

- duration of outburst (Δt_{MRI})
- how often an outburst happens (T_{EA})

$\Delta t_{MRI} << T_{EA}$

$T_{EA} > t_{dyn} \sim 10^3 yr$



Duration of episodic accretion event

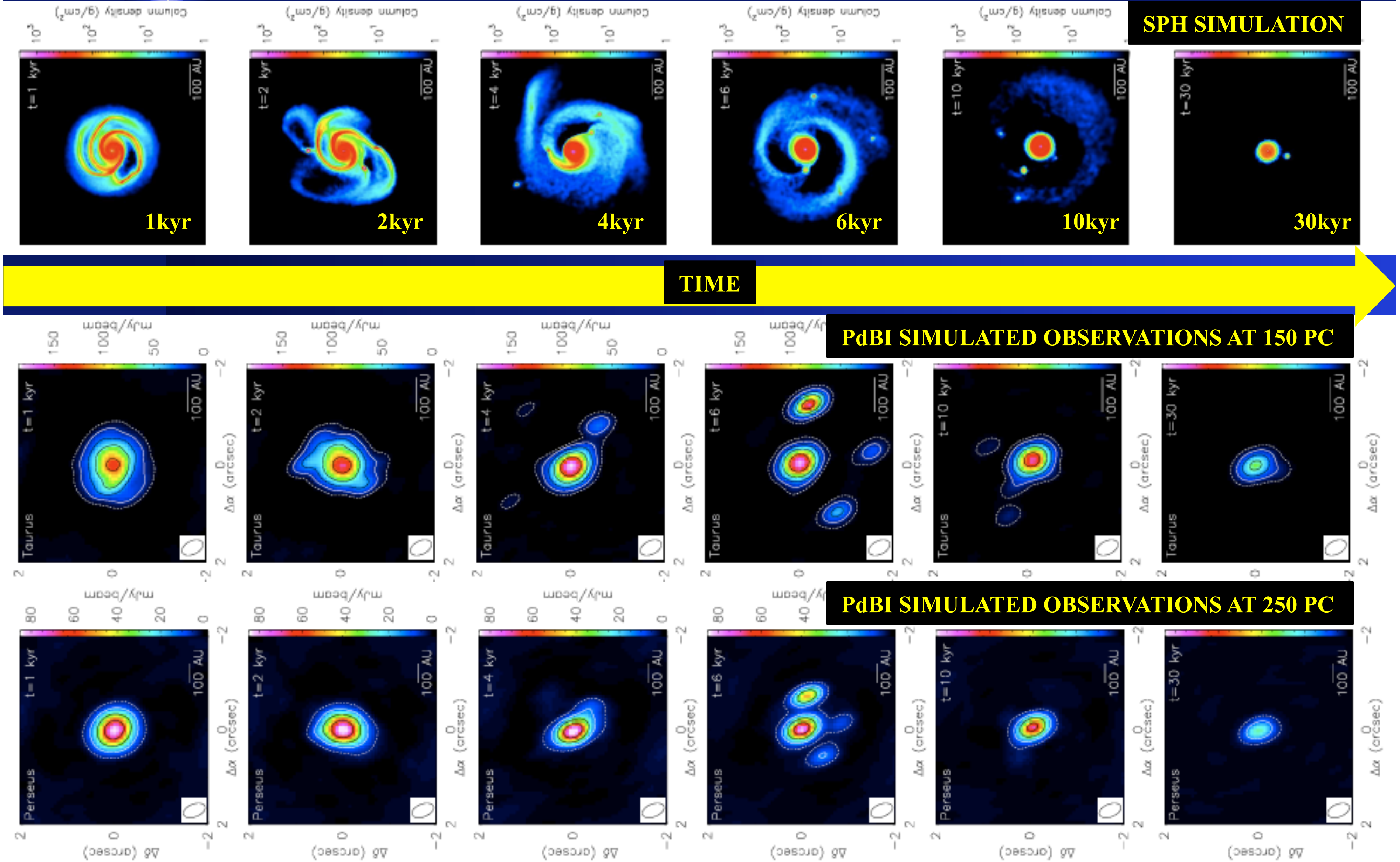
$$\Delta t_{\rm MRI} \simeq 0.25\,{\rm kyr}\,\left(\frac{\alpha_{\rm MRI}}{0.1}\right)^{-1}\left(\frac{M_{\rm MRI}}{0.13\,{\rm M}_\odot}\right)$$

Time interval between successive episodic accretion events

$$T_{\rm EA} \simeq 13\,{\rm kyr}\,\left(\frac{M_\star}{0.2\,{\rm M}_\odot}\right)^{2/3}\left(\frac{\dot{M}_{\rm IAD}}{10^{-5}\,{\rm M}_\odot\,{\rm yr}^{-1}}\right)^{-8/9}$$

Observing fragmenting discs

Stamatellos, Maury et al. 2011, MNRAS



SPH SIMULATION

TIME

PdBI SIMULATED OBSERVATIONS AT 150 PC

PdBI SIMULATED OBSERVATIONS AT 250 PC

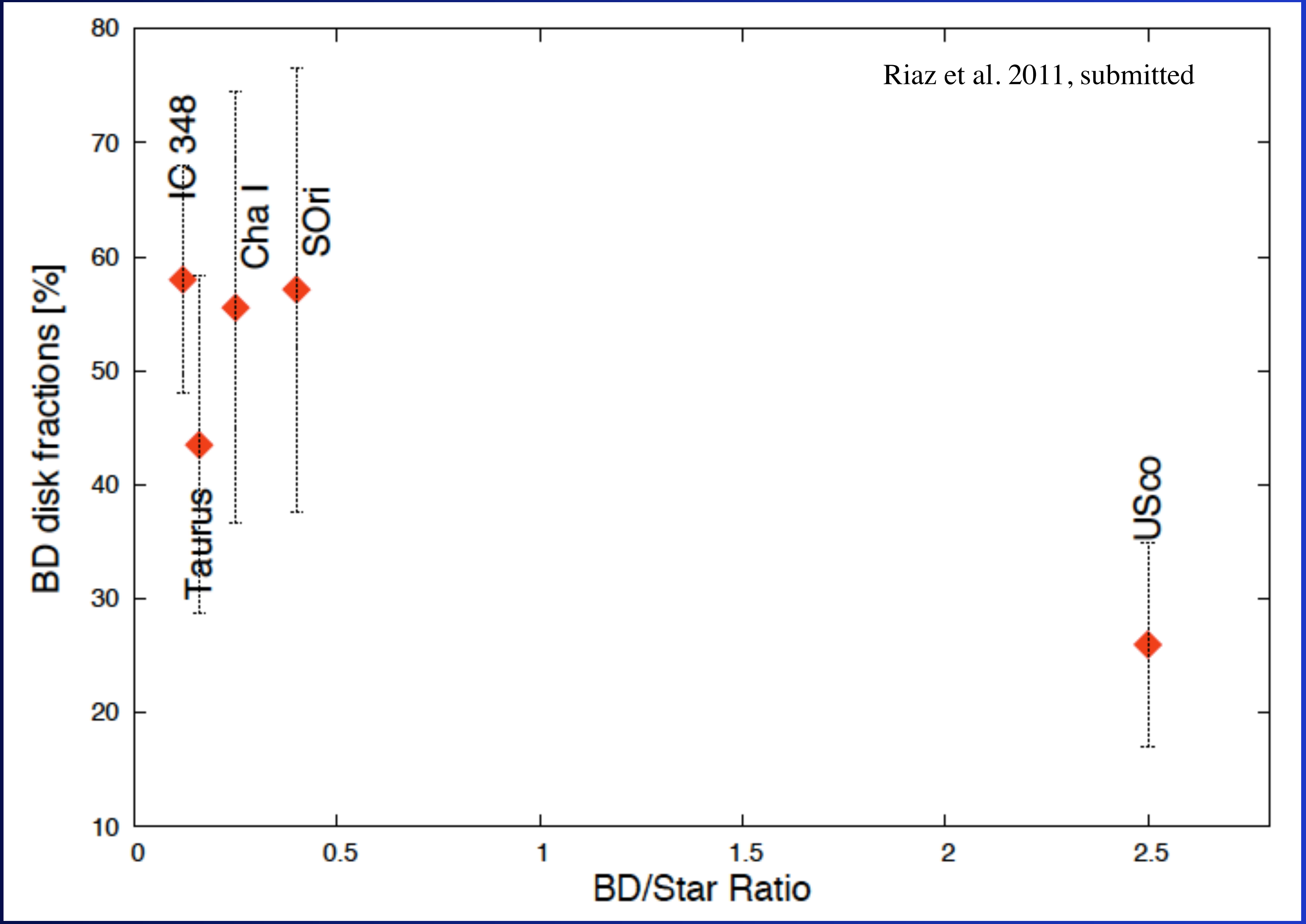
Concluding remarks

- Episodic radiative feedback (due to episodic accretion) limits considerably the effects disc heating by the protostar

- Disc fragmentation is still possible; discs fragment to form low-mass stars, brown dwarfs and planetary-mass objects

- The frequency of episodic accretion events may regulate low-mass star formation in different environments; where accretion events are more frequent (e.g. in high-density regions) fewer low-mass stars are expected.

Different mechanisms may dominate in different regions?



Observing the early stage of fragmenting discs is possible but improbable due to duration of the process

- $\Delta t_{\mathrm{FRAGM}}=1.5\times10^{4}$ yr
- $\Delta t_{\mathrm{CLASS\ 0}}=1.5\times10^{5}$ yr
- 10% of young protostars have such discs (enough to give 50% of the brown dwarf population)

⇩

- ~1% of Class 0 objects should have large unstable discs